MEASUREMENTS OF TOP QUARKS PRODUCED IN PAIRS AT D0

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We report on current D0 top quark measurements obtained using 350 to 900 pb^{-1} of data collected using $t\bar{t}$ candidates selected in various decay channels. These include $t\bar{t}$ production cross section measurements in all channels (lepton+jets, dilepton, and all jets), and top quark mass measurements using various methods in lepton+jets and dilepton final states.

1. Overview

Top quarks are produced in pairs via the strong interaction. At the Tevatron, operating at 1.96 TeV in Run II, the expected production rate of $t\bar{t}$ pairs is 6.8±0.6 pb @ m_t=175 GeV/c^2.[1] Roughly 85% arise from $q\bar{q}$ interactions, while the remaining 15% are created by gluon fusion. As of February 4, 2007, 2.05 fb^{-1} of data have been recorded by the D0 experiment.

To study the properties of the top quark, events are separated according to the types of decays of the $t\bar{t}$ pairs. Each top quark decays almost exclusively to a W boson and a b quark. The W boson then decays either to a lepton and neutrino or to two quarks. Classification of events is done according to the particles in the final state: *dilepton*, *all jets*, or *lepton+jets*.

"All jets" events make up approximately 54% of $t\bar{t}$ events. Top quark measurements benefit from the larger statistics of this channel, but, unfortunately, the QCD multijet background is also very large. Jet energy scale uncertainties are also largest for this channel, making the all jets channel difficult for top quark measurements. Dilepton events have fewer jets in the final state and an easily identifiable Z+jets background, but much smaller statistics – only 7% of $t\bar{t}$ events are dilepton events. We find the best combination of statistical and systematic uncertainties for top quark measurements in lepton+jets events.

2. Cross-section Measurements

2.1. *Lepton+jets channel*

The lepton+jets channel is characterized by a single high transverse momentum (p_T) electron or muon in the final state, significant missing transverse energy ($\not\!\!E_T$), and at least four high p_T jets. The contribution from the QCD multijet background is estimated directly from the data sample. A topological discriminant is used to form a likelihood, which is then maximized to determine the production cross-section. The discriminant is constructed from six kinematic variables, chosen to give the best discrimination possible between signal and background while minimizing the uncertainties due to jet energy scale. The final result for the 900 pb^{-1} data sample is $\sigma_{t\bar{t}} = 6.3\ ^{+0.9}_{-0.8}$ (stat) $\pm\,0.7$ (syst) $\pm\,0.4$ (lumi) pb, with the largest source of systematic uncertainty coming from the simulation of the W+jets background.

b-tagging techniques are used to identify events with jets likely to have arisen from the hadronization of b-quarks, significantly decreasing the W+light-flavor jet background. Two different b-tagging methods are used on a 425 pb^{-1} lepton+jets sample: 1) a *Secondary Vertex Tagging* (SVT) algorithm, which identifies the vertices displaced from the primary interaction vertex, and 2) *soft muon tagging*, identifying b-jets by the presence of soft muons within the jets. The SVT b-tagging analysis uses the selection efficiencies, determined using Monte Carlo-simulated events, to determine the most likely numbers of signal and background events.[2] The final and best result to date at D0 for $\sigma_{t\bar{t}}$ is 6.6 $\pm\,0.9$ (stat + syst) $\pm\,0.4$ (lumi) pb. Uncertainties in cross-sections of the various heavy-flavor W+jets backgrounds, as well as differences between b-tagging in Monte Carlo and data, both dominate the systematic uncertainty.

The result obtained with soft muon tagging is expected to be less precise because of the lower b-tagging efficiencies and higher mistag rate, but it provides a consistency check nonetheless. The result on the 425 pb^{-1} lepton+jets data sample is $\sigma_{t\bar{t}} = 7.3\ ^{+2.0}_{-1.8}$ (stat + syst) $\pm\,0.4$ (lumi) pb.

2.2. *All jets channel*

The $t\bar{t}$ production cross-section is measured using a neural network on a 405 pb^{-1} data sample using fully hadronic $t\bar{t}$ decays.[3] Six kinematic parameters are used as input to the neural network to give discrimination between signal and the very large QCD multijet background. Monte Carlo-simulated $t\bar{t}$ events are used for signal, while data events with no b-tagged jets are used for background in training the neutral network. SVT b-tagging is used with a neural network cut to reduce the background-to-signal ratio.

The overwhelmingly large QCD multijet background allows us to use the entire sample to estimate the background contribution to the b-tagged sample. This is done by parametrizing the b-tag rate functions using the entire data sample, and weighting events that have neural network values away from the $t\bar{t}$ peak. The number of background events is chosen to achieve the proper number of events in the single- and double-tagged data samples. The final result is $\sigma_{t\bar{t}} = 4.5\ ^{+2.0}_{-1.9}$ (stat) $^{+1.4}_{-2.1}$ (syst) ± 0.3 (lumi) pb.

2.3. *τ+jets channel*

Understanding the τ+jets top quark decay channel is important for two reasons. Firstly, charged Higgs can decay to τ leptons. Secondly, non-standard flavor- and mass-dependent couplings are easier to see in decays of top quarks to the heavier τ leptons.

Roughly 65% of τ decays are to final states containing hadrons. These decays are classified according to the most likely type of τ-decay: 1) π-type ($\tau \rightarrow \pi^- \nu_\tau$), 2) ρ-type ($\tau \rightarrow \rho^- \nu_\tau \rightarrow (n\pi^0 + \pi^-)\nu_\tau$), and 3) "3-prong" decays, which are decays to 3 charged hadrons and possibly neutral hadrons. A separate neural network is trained for each type of τ decay, and these neural networks are used to help identify events with τ leptons. At least 1 SVT b-tagged jet is required to enhance the $t\bar{t}$ fraction in the data sample. The final result for this channel with 350 pb^{-1} of data is $\sigma_{t\bar{t}} = 5.1\ ^{+4.3}_{-3.5}$ (stat) ± 0.7 (syst) ± 0.3 (lumi) pb.

3. Top Quark Mass Measurements

3.1. *Lepton+jets channel*

The most precise measurements of the top quark mass to date have been done using the *Matrix Element* method.[4] This method uses likelihoods for the event, assumed to be proportional to the differential cross-section, dσ, for the relevant signal or background physics process. dσ is determined by integrating the scattering amplitude, $|\mathcal{M}|^2$, over the phase space of the partons in the initial and final state. The integration is over all kinematically allowed parton momenta, with a weight determined from the measured momenta and known detector resolutions. Parton distribution functions are folded into the integration over incoming quark momenta.

The leading systematic uncertainty in the top quark mass measurement arises from uncertainties in jet energy scale (JES). The overall JES is allowed to vary, giving a likelihood which depends upon both top quark mass and JES. Maximizing the likelihood with respect to both variables simultaneously reduces the systematic uncertainty with respect to JES.

The signal probabilities are calculated using a leading order $t\bar{t} \to l\nu b\bar{b}qq'$ calculation. The background probabilities are calculated using a VECBOS-based matrix element. b-tagging is used in the assignment of jets measured in the detector to the four quarks in the final state to improve the measurement. Overall likelihoods are also determined separately for events with 0, 1, or $\geq$ 2 b-tagged jets using SVT b-tagging. Figure 1 shows the likelihood for the events with two or more b-tags. The final result for all events in the 370 pb^{-1} data sample is: $m_t = 170.3\,^{+4.1}_{-4.5}$ (stat + JES) $^{+1.2}_{-1.8}$ (syst) GeV/c^2.

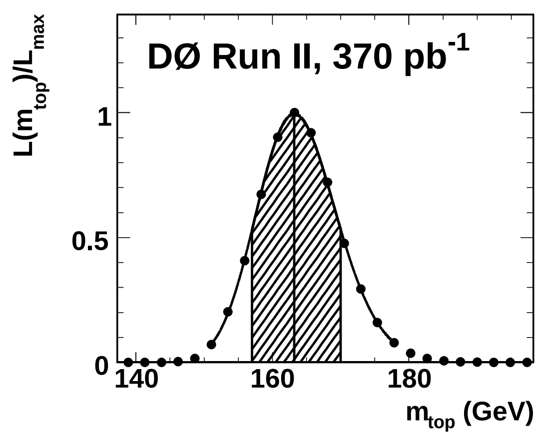

Figure 1. Likelihood vs. m_t for double b-tagged l+jets events.

With the *Ideogram* method, performed on the same data sample, the signal probability for a particular mass hypothesis is obtained by integrating a Breit-Wigner likelihood over all possible top quark masses.[5] Gaussian detector resolutions are folded into the integration to allow for differences between measured and actual final state momenta. The background probability uses the shapes of mass distributions for Monte Carlo-generated W+jets events. SVT b-tagging is used to weight the various ways of matching jets to final-state partons. The likelihood is calculated as a function of top quark mass and JES to give the following result, consistent with the result obtained using the Matrix Element method: $m_t = 173.7\ \pm 4.4$ (stat + JES) $^{+2.1}_{-2.0}$ (syst) GeV/c^2.

3.2. *Dilepton channel*

Measurements in the dilepton channel are slightly more difficult due to the presence of two neutrinos in the final state. With measurements of 4 final state particle momenta and $\not\!\!E_T$, constraining the lepton-neutrino invariant mass to be the W boson mass, and requiring the two top quark masses to be equal, 17 of the 18 parameters required to solve the event kinematics are known. Two different methods are used to measure the top quark mass in the dilepton channel using 835 pb^{-1}.

The *neutrino weighting* method removes the measured $\not\!\!E_T$ as a constraint, leaving three undetermined parameters. Then, for a given m_t hypothesis, a series of pseudorapidities are used for each neutrino to obtain a kinematic solution. The solution is then weighted according to the agreement of the calculated $\not\!\!E_T$ with the measured $\not\!\!E_T$. The weighted sum of likelihoods for each top mass hypothesis is used to form an overall likelihood. The result with this technique is $m_t = 171.6 \pm 7.9$ (stat) $^{+5.1}_{-4.0}$ (syst) GeV/c^2.

The *matrix element weighting* method calculates the event likelihood for a particular m_t hypothesis using the probabilities for the leptons to have their measured momenta. Probabilities are calculated using the matrix element. Parton distribution functions are folded into the event likelihood as well for various incoming parton momentum fractions. The final result of using the matrix-element weighting method in the dilepton channel is $m_t = 177.7\ \pm 8.8$ (stat) $^{+3.7}_{-4.5}$ (syst) GeV/c^2.

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